COGNITIVE PSYCHOLOGY **33,** 88–110 (1997)
ARTICLE NO. CG970661

Brain Plasticity in Learning Visual Words

Bruce D. McCandliss, Michael I. Posner, and T. Givón

Departments of Psychology and Linguistics, University of Oregon

This study used event-related brain potentials and performance to trace changes in the underlying brain circuitry of undergraduates who spent 5 weeks learning a miniature artificial language. A reaction time task involving visual matching showed that words in the new language were processed like nonsense material before training, and like English words at the end of the 5 weeks of training. Scalp electrical recordings were used to explore the underlying basis for the change due to learning. Results of the ERPs were consistent with brain imaging studies showing posterior areas related to visual orthography and more widespread left lateral frontal and temporal areas related to semantic access. A posterior component at about 200 ms proved sensitive to differences in the orthography but did not change over the course of 5 weeks of training. A later ERP component at about 300 ms was sensitive to semantic task demands and underwent changes over the 5 weeks that were congruent with training-related changes observed in subjects' matching task performance. © 1997 Academic Press

INTRODUCTION

This paper presents an approach to investigating a complex human skill by studying changes in brain processes that are associated with learning. Reaction time and electrophysiology (ERP) methods are used to trace changes that take place in cognitive operations and neural responses as subjects learn to recognize words of this language.

To carry out this study we used Keki, a miniature artificial language of 68 words constructed for the purposes of this study (Yang & Givón, 1993). Over the course of 5 weeks Keki was taught to a group of subjects via a computerized training procedure. During the 5 weeks of learning, subjects progressed from complete unfamiliarity with the Keki words to a level of fluent word identification that matched their performance on English.

Cognitive models of word recognition propose component operations that act on different mental codes (See Carr & Pollatsek, 1985; Jacobs & Grainger, 1994,

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This paper was supported in part by grants from the W. M. Keck Foundation and from the James S. McDonnell Foundation and Pew Memorial Trusts to the Center for the Cognitive Neuroscience of Attention and the Office of Naval Research Contract 00014-96-0273.

Reprint requests should be addressed to Bruce D. McCandliss at 640 Learning Research and Development Center, 3939 O'Hara St., University of Pittsburgh, Pittsburgh, PA 15260.

0010-0285/97 $25.00

for discussion). In this paper we focus on orthographic and semantic codes that have been investigated by both cognitive and neuroimaging methods.

Orthography

When stimuli are presented briefly and then masked, people are generally better at recognizing letters that appear in a word than letters that appear in a random letter string (Cattell, 1886; Reicher, 1969). This result was termed the ‘‘word superiority effect’’ and was the subject of a great deal of investigation. Similar processing benefits have been observed for orthographically regular letter strings that do not form words, suggesting that at least part of the word superiority effect could reflect a subject’s experience with a particular orthographic system (for review see Carr and Pollatsek, 1985). Word and pseudoword superiority effects have also been observed in visual matching tasks, suggesting that orthographic experience could influence the formation of visual codes as subjects view letter strings (Carr, 1986).

PET studies have been used to investigate the brain mechanisms involved in word recognition. The rationale behind these studies is to localize regions which become more active (measured through significant changes in cerebral blood flow) during particular word recognition tasks. The aim is to identify brain regions associated with the functional components of word recognition suggested from cognitive research.

One set of studies (Petersen, Fox, Snyder, & Raichle, 1990) investigated the cortical regions associated with processing letter strings. Sets of stimuli were passively viewed during separate scans. One set formed familiar English words, another formed consonant strings, and a third formed orthographically regular nonwords. To image cortical regions specifically related to processing letter strings, a fixation-only baseline condition was subtracted from all three string types.

All subtraction images indicated several cortical regions activated above baseline. However, a left medial region of extrastriate cortex (at the occipital temporal boundary) was activated by letter strings which formed either familiar words or orthographically regular pseudowords, but was not activated above baseline by consonant strings. (Petersen *et al.*, 1990). This localization has been supported by depth recording from patients (Nobre, Allilson, & McCarthy, 1994). Apparently, this region of visual cortex is sensitive to the orthographic regularity of a letter string, yet not sensitive to whether a letter string corresponds to a specific word representation.

One of the limitations of using PET imaging to study word recognition involves the fact that word recognition is a rapid mental process, yet creating a single PET image typically requires many seconds of processing. Event-related potentials (ERPs) provide a millisecond by millisecond record of electrical activity under each experimental condition. By recording ERPs with a dense array of many sensors on the scalp, information can be obtained about which sensors in the array first discriminate between two experimental conditions.

Compton, Grossenbacher, Posner, and Tucker (1991) used a 32-channel array of sensors to characterize the ERPs associated with the perception of orthographically regular words and consonant strings. In two separate experiments (Compton *et al.*, 1991) ERPs in the posterior regions of the array were the first to show a difference between words and consonant strings by 150 to 225 ms after presentation of the letter string. This effect was also found to be somewhat stronger in channels over the left hemisphere than in channels over the right.

These results are suggestive of a left lateralized region that is sensitive to the orthographic regularity of letter strings and which acts as an initial processing gateway to word recognition. In our study, we contrast the early posterior ERP effects for English words, orthographically illegal strings, and novel letter strings that are orthographically similar to English in order to strengthen the link between this posterior ERP effect and the extrastriate activation indicated by the PET studies.

Semantic Processing

One of the central processing goals of a fluent reader is to access meaningful information corresponding to the visual words being read. Cognitive research (Meyer and Schvanevelt, 1971, 1976) has used priming to examine semantic access during word recognition and thus address the relationship between stimulus driven semantic activation and semantic activation related to attention. One line of research has demonstrated semantic priming under conditions that mask the prime so quickly after its presentation that subjects can no longer accurately report seeing the prime word (Marcel, 1983; Carr & Dagenbach, 1990; Dagenbach, Carr, & Wilhelmsen, 1989; Fuentes and Tudela, 1992; Fuentes, Carmona, Agis, & Catena, 1994). These experiments demonstrate that semantic activation of a prime word's meaning does not necessarily depend on first becoming aware of the prime word's identity. However, the task demands placed on a visual word can have a substantial impact on semantic priming (Smith, Theodor, & Franklin, 1983). Friedrich, Henik, & Tzelgov (1991) obtained semantic priming when subjects were required to name each prime, but no semantic priming occurred when subjects had to search for a letter in the prime. Friedrich *et al.* (1991) demonstrated that these same prime task manipulations had very little impact on repetition priming effects, demonstrating that prime task manipulations have the most influence over word recognition components involved in semantic access rather than other component processes.

PET studies (Howard, Patterson, Wise, Brown, Fristen, Weiller, & Frackowiak, 1992; Petersen *et al.*, 1990; Raichle, Fiez, Videen, MacLeod, Pardo, and Petersen, 1994) and fMRI studies (McCarthy, Blamire, Rothman, Gruetter, & Shulman, 1993) have also attempted to examine differences between actively processing the meaning of a visual word and simply viewing or naming a word. These studies have involved subtracting control reading tasks from tasks that either require the subject to generate the use of a given noun, or that require them to classify nouns into semantic categories. These studies have shown that the additional semantic processing associated with the generate or classification tasks activates a network of areas including mid frontal (anterior cingulate) and left frontal (areas 45 and 47) and left posterior (Wernicke's area) cortical areas and the right cerebellum.

When practice on a particular word list automates subjects' responses in the generate task, the network of activations typically seen in the generate task disappears and the anatomy involved in the well-practiced generate task largely resembles the anatomy activated by the control task of reading words aloud (Raichle *et al.,* 1994). This practice study provides further evidence that the network of areas active by the unpracticed version of the generate task are related to effortful semantic processing.

While there has been reasonable agreement about the areas activated by semantic processing in the generate task, little consensus has been reached on the different functional roles played by each of these areas. The cingulate activation has been proposed to be related to general attention demands, since it also occurs in many nonsemantic tasks. However, the role for the other cortical and cerebellar activations is still unclear.

To study the functional role of regions associated with increased semantic processing, ERPs have been recorded when subjects either generate a use for a visually presented noun or simply read the noun out loud (Abdullaev & Posner, 1997; Snyder, Abdullaev, Posner & Raichle, 1995). The generate task produced an increased positivity over left inferior frontal regions peaking about 230 ms, followed by an increased positivity over left posterior temporal regions at about 600 ms.

Brain electrical source analysis was used to fit to the scalp voltage distribution by a set of dipole generators (Scherg & Berg 1990). The increased positivity recorded around 230 ms was best simulated by two dipoles corresponding roughly to the anterior cingulate gyrus and the left prefrontal area indicated in the PET studies of the same tasks. The increased positivity occurring about 600 ms after stimulus onset was best accounted for by a single dipole located in a left mid temporal area near Wernicke's area.

Taken together, the semantic priming studies, PET studies and the ERP study suggest that increased attention to word meanings should increase activation in left frontal and posterior semantic areas and increased attention to the visual features of words should attenuate activation in these same areas.

LANGUAGE LEARNING

Studies of the changes which take place over the time course of skill learning have provided important insights into the cognitive and neural processes involved (LaBerge & Samuels, 1974; Raichle *et al.,* 1994; Seidenburg & McClelland, 1989). Our study examines the impact of learning on processing a set of novel words. We use methods for studying language

FIG. 1. Example of training stimuli used in the early lessons of the interactive computer tutorial.

learning under controlled testing conditions that have been developed through research on miniature artificial languages (Esper, 1925; Mori, 1991).

The Keki Language: Stimuli and Training

The Keki lexicon consisted of 68 pronounceable words corresponding to meaningful objects, properties, and events depicted in a set of line drawings used during training. Each Keki word corresponded to a direct translation of a high frequency English noun, verb or adjective (See Appendix). The Keki word form pattern can be formalized as a C(C)VC(C)V[1] system. The orthographic system used to form Keki words is similar to English orthography in several ways. However, the Keki word form system differs from English in that all words are vowel final, and may contain bigrams and trigrams that are uncommon in English orthography (i.e., liska, dimo, and gilki). These unique features of Keki orthography create an interesting intermediate test case for measures related to orthographic processing, as Keki contains several orthographic qualities in common with English as well as some orthographic qualities that are distinct from English.

Each subject spent a total of 50 hours learning the Keki language from a set of interactive computer tutorials. The course of training spanned 5 weeks and required 5 days of participation per week for 2 hours a day. The computer tutorials emphasized direct relationships between visual presentation of Keki words and a ‘‘reference field’’ that consisted of line drawings depicting objects, characters, and actions. In the initial lessons, the pictures depicted simple objects in isolation or in small groups (see Fig. 1), and gradually increased in complexity

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[1] C represents a consonant from the set {b, c, d, f, g, k, l, m, n, p, r, s, t, z} and V represents a vowel from the set {a, e, i, o, u}. Letters marked in parentheses are possible elements in the Keki word form, but are not mandatory.

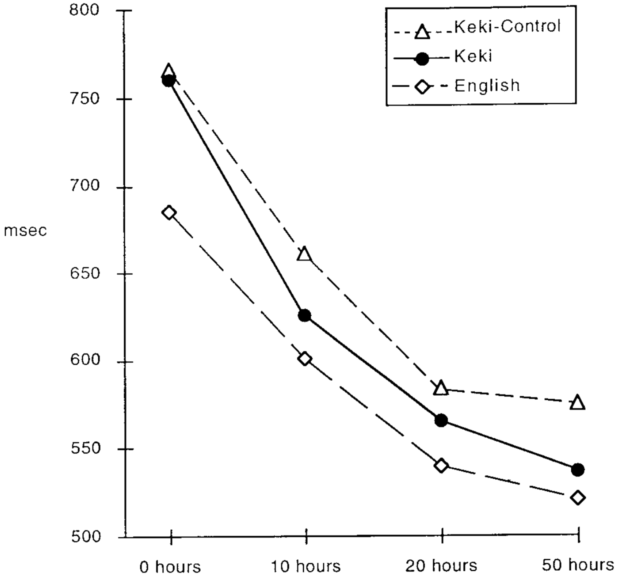


FIG. 2. Mean reaction times (in ms) for a letter string matching experiment conducted by Yang and Givón (1993).

as the lessons progressed. Eventually Keki sentences and their corresponding reference fields progressed to a level of complexity that included descriptions of situations that involved characters interacting with objects and other characters.

Cognitive Measures of Keki Learning

At several intervals during the course of training, subjects performed a letter string matching task to track the time course of word recognition of Keki words (Yang & Givón, 1993). The strings in the matching task consisted of familiar English words, Keki words, or Keki control words. Keki control words were constructed to reflect Keki words in orthography and length, but were not part of the training set. The matching task was performed on two serially presented letter strings separated by a 1-s interval. Each letter string appeared for 87 ms followed by a mask, and subjects were to respond as quickly as possible whether the same letter string was presented twice. To prevent matching on the basis of visual similarity alone, the two-letter strings were presented in opposite letter cases.

Results from the matching task are presented in Fig. 2. As expected, there were no differences between performance on Keki words and Keki control strings during the initial test. However, subjects responded approximately 80 ms faster to letter strings that formed English words. The reaction time benefit for English strings over the Keki and Keki control strings during the initial visit might reflect the fact that only the English strings had preexisting representations, although it is also possible that these performance differences could be related to orthographic differences between these classes of stimuli.

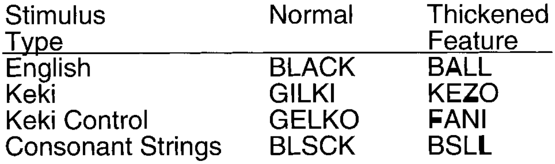
As this test was repeatedly administered over the course of the training program, overall reaction times generally decreased for all three stimulus types. Presumably this overall improvement in reaction times reflects practice effects related to learning the matching task. However, reaction times to Keki words improved more rapidly across the four testing sessions than did reaction times to the other two string types. After 50 hours of Keki training, subjects responded to both English words and Keki words more rapidly than to Keki control strings. No significant differences existed between response times for Keki and English strings. Note that the Keki words and the Keki control strings were matched for length and orthographic regularity, so any differences between Keki and Keki control words can only be attributed to the development of specific representations related to Keki words rather than differences in orthographic regularity.

ERP EXPERIMENT

In addition to the matching task, subjects participated in three ERP testing sessions that took place before, during, and after the 5 weeks of training. The purpose of the ERP experiment was to trace learning-related effects in cortical responses to novel words. Specifically, the ERP experiment was designed to investigate changes across the training sessions related to both orthographic encoding processes and processes related to semantic access.

To assess orthographic effects, one additional set of stimuli was included in the ERP experiments that did not appear in the matching task. In addition to English, Keki words and Keki control strings, a set of unfamiliar, orthographically illegal consonant strings was included. Thus on a dimension of orthographic regularity, the English strings used in this study represent exemplars of orthographic regularity, the consonant strings represent gross violations of English orthography, and both the Keki words and the Keki-control strings represent an intermediate level of orthographic regularity by the standards of English orthography. If early ERPs collected over posterior regions of the brain during the first 200 ms of processing are sensitive to the orthographic regularity of a letter string, then the stimulus groups described should produce three graded levels of ERP responses. Such effects would be consistent with the hypothesis that early ERP responses over posterior areas of the brain are sensitive to orthographic processing. Furthermore, examination of changes in ERP responses to Keki words and Keki control words over the course of 5 weeks of learning provides an opportunity to trace orthographic learning as adults learned to fluently recognize the Keki orthography.

Secondly, to assess processing related to semantic activation, the ERP experiment presented each of the stimuli under three different task demands: passive viewing, a semantically demanding judgment task, and a feature search task. As mentioned above, a number of semantic priming studies and neuroimaging



Stimulus Type	Normal	Thickened Feature
English	BLACK	BALL
Keki	GILKI	KEZO
Keki Control	GELKO	FANI
Consonant Strings	BLSCK	BSLL

FIG. 3. Examples of stimuli used in the Keki ERP experiment.

studies suggest that semantic representations can be activated while passively viewing a word, but these activations can be enhanced by adding task demands related to the meaning of a word or they can be attenuated by adding task demands that focus subjects' attention on individual letter features. This task manipulation was incorporated into the design of the ERP experiment to record such differences in semantic activation within an ERP paradigm, and to use these differences in semantic processing as a means to trace the development of semantic representations associated with newly learned Keki words.

METHODS

Subjects

Subjects were required to be monolingual English speakers enrolled in an undergraduate program at the University of Oregon with a cumulative GPA of 3.0 (B) or higher. Subjects who completed more than 1 year of formal foreign language training or had lived in another country for over a year were excluded from the study. A total of 19 subjects participated in at least the initial ERP session in exchange for payment of $6.00 per hour. Twelve of these initial subjects (8 female, 4 male) participated in all three ERP sessions. Only data from these 12 subjects is considered below.

Stimuli

The same set of stimuli (letter strings between four and six letters long) were used for all three task conditions. Sixty Keki words were selected from a larger set of 68 in the Keki lexicon (Yang & Givón, 1993), and 60 Keki control strings were constructed to match the length and orthography of the 60 Keki words. In addition, 88 English words were selected, and 60 consonant strings were produced by replacing each vowel in the list of English words with a consonant of roughly equivalent letter frequency. English and Keki stimulus groups were created such that half were judged by three independent raters to have a tangible referent (something that could be both seen and touched), and half were judged to have referents that were intangible.

Half of the stimuli in each of the stimulus groups (tangible English, intangible English, tangible Keki, intangible Keki, Keki-control, consonant strings) were selected at random for a letter feature manipulation. A font manager program was used to make one-letter segment of one letter in each selected string appear thicker than the other letter segments. Altered letter segments were evenly distributed across the letter positions within each string. Sample stimuli used in the ERP experiment are presented in Fig. 3.

Procedure

Each subject participated in the ERP testing procedures three times during three separate sessions—once before any exposure to Keki, once after 20 h of instruction (10 days of training spaced over 2 weeks), and once again after 50 h of total instruction (25 days of training spaced over 5 weeks). The testing sessions for the 20-h training interval were run within the 3-day period between the 10th and 11th day of training, and testing sessions for the 50-h training interval were run within 4 days of the last day of training. The same experimental procedure was followed for each of the three testing sessions except where noted.

Following application of the electrode array (20–30 min), subjects entered an electrically shielded and sound attenuated booth. Once inside, they placed their index fingers on the left and right keys of a two-key response pad. One key (counterbalanced across subjects) was designated as the ‘‘target’’ key, and remained so throughout all three experimental sessions. A chin rest situated approximately 75 cm from a monochrome computer monitor helped subjects remain still throughout the experimental session.

Stimulus presentation parameters were identical in each trial of the experiment. Trials began with presentation of a fixation cross, subtending .87 degrees of vertical and horizontal visual angle, centered on a computer screen. To reduce artifacts in the EEG measurements associated with anticipating the onset time of the letter string, the duration of the fixation cross was varied randomly from 185 to 750 ms. Then the fixation cross was replaced by one of the four types of letter strings (English, Keki, Keki control, or consonant string) selected at random. The letter string subtended .87 degrees vertically and between 1.75 and 3 degrees horizontally. After 765 ms the letter string was replaced by another fixation cross which remained until the subject responded by pressing one of the two keys. This interval was chosen to avoid introducing any response execution or visual events that could affect the EEG signal between stimulus onset and the following 750 ms. Subjects were instructed to withhold responses until the stimulus word was replaced by the fixation cross. A 1000 ms recording of EEG collected at 125 Hz was made during each trial, beginning 185 ms prior to the onset of the letter string, and ending shortly after the offset of the letter string.

Trials within each of the three ERP sessions were divided into three task blocks. The only difference between the three task blocks during each ERP session was the instructions that were read to subjects before beginning each block. In the passive task subjects were instructed to fixate their eyes on each letter string, but to relax and not exert any mental effort while the stimulus was present. When the string was replaced by a fixation cross, they were to advance to the next trial by pressing the target key. A semantic task required subjects to decide whether the string ‘‘represented something tangible or not.’’ They were told that in this context, ‘‘tangible’’ is used to refer only to things that can be seen and touched. When the word was replaced by a fixation cross they were to enter the conclusion of their decision by pressing the target key for strings that represented something tangible, and pressing the non-target key for all other strings. The feature search task required subjects to decide whether the string contained a thickened letter segment and to register their decision after the fixation cross replaced the string.

After receiving instructions for the block, subjects completed 30 practice trials containing examples of all four types of stimuli. Practice trials were followed by feedback on the accuracy of performance. After the practice trials, subjects completed the block of experimental trials without feedback.

The order of the semantic and feature task blocks was counterbalanced across subjects.[2] Each block consisted of 268 experimental trials with the exception of the three blocks in the first testing session. Since the Keki letter strings had no meaning to the subjects before their formal instruction began, 88 additional filler English words were included in the stimulus sets to roughly equalize the number of words to non-words appearing across the three testing sessions.

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[2] The passive block was always presented in the first position to avoid strategic carryover effects. Therefore, differences between the passive task and the other two tasks could be attributable to order effects, effects of stimulus repetition, and/or genuine task effects.

ERP Recording

ERP responses were collected at the three testing intervals to assess the stability of the basic stimulus and task contrasts mentioned above, and to allow learning related changes to be examined in the context of control conditions which assess orthographic and semantic processing.

EEG was recorded with a 64 sensor Geodesic Electrode Net (Tucker, 1993; Tucker, Liotti, Potts, Russell, & Posner, 1994). The net consists of 57 sponge tip sensors that rest on the subject's scalp, passing current through a saline solution to a Ag/AgCl electrode embedded in each sponge. Elastic threads connect each adjacent sensor in the array, forming a network of sensors and elastic threads in a geodesic pattern. This geodesic arrangement of elastic tension between the sensors provides an even spatial distribution of sensors over the superior scalp surface (the scalp surface superior to the plane formed by the two external canthi and auditory meati). In addition to the sponge-tipped electrodes, external Ag/AgCl electrodes were attached to the nasion site, two external canthi sites, two inferior orbital sites, two mastoid sites, and a ground site located on the back of the neck (see Fig. 5A for a polar diagram of electrode placement sites). The signal from channel 65 is reconstructed based on the inverse of the average voltage across the entire array (see Tucker *et al.*, 1994).

Each electrode was tested to be below 40 Kohm before each session. Although such impedance values are higher than in many ERP studies, high impedance amplifiers were used in this study which allowed recording at higher electrode impedance values than those used in previous studies. Signals were amplified using a 0.1 Hz to 50 Hz (3 dB) bandpass followed by a 60-Hz notch filter and were digitized using a 16-bit A/D converter at 125 cycles per second. Data were initially stored on computer disk in the form of right mastoid referenced EEG.

After data collection, each 1-s epoch of data for each of the 64 channels in the array was examined by coders blind to the experimental conditions for signs in the EEG indicating artifacts such as eye movements, blinks, or muscle movements. This procedure resulted in rejection of approximately 15% of trials, distributed roughly equivalently across session, block, and stimulus conditions. The remaining data was then averaged for each subject to form one ERP epoch for each of the 64 channels in each of the experimental conditions (session × task block × stimulus type).

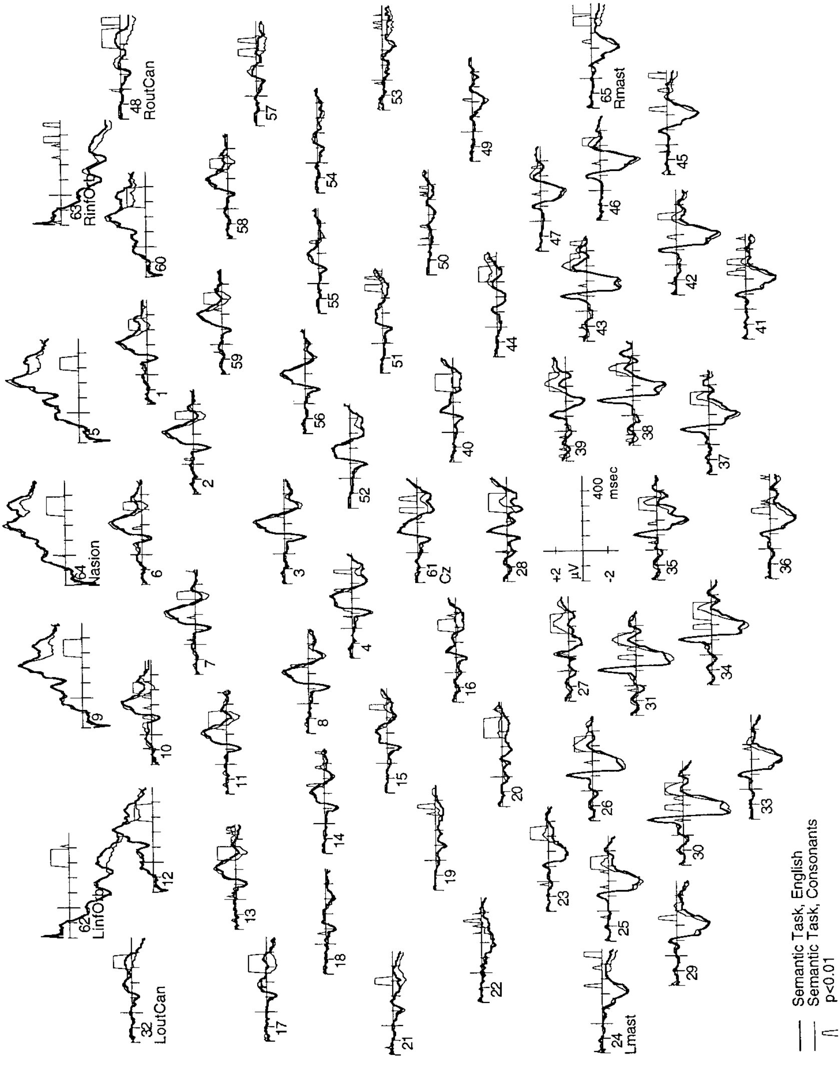
Average Reference Transform

Although the data were originally collected in a form referenced to a specific mastoid site, when the data are in this form, each sensor in the entire array can be influenced by any activity which affects the reference site. To minimize this influence, an average reference transform was applied to the ERP data (Lehmann and Skrandies, 1985) which allowed the ERP recorded at each sensor location to be rereferenced with respect to an estimate of the average voltage over the entire superior scalp surface.

RESULTS

Preliminary Analyses

The ERP data collected formed a large array of data, composed of 65 channels × 125 samples × 12 subjects for each of the experimental conditions. A preliminary analysis was conducted to construct appropriate dependent measures from the ERP data set that could be used to systematically quantify and analyze changes in orthographic and word-specific processing as subjects learned the Keki words. This preliminary analysis consisted of a 65 channel, sample by sample Wilcoxon Signed Rank Test applied to the averaged ERP data. Tests were restricted to a comparison between two experimental conditions: English vs consonant string stimuli viewed within the semantic task. These two conditions represent the extreme cases of meaningful lexical items


63 RinfOb
48 RoutCan
57
53
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65 Rmast
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1
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64 Nasion
2
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42
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52
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39
38
37
6
3
61 Cz
28
+2 µV -2
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26
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62 LinfOb
12
13
14
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23
25
30
29
32 LoutCan
17
18
21
22
24 Lmast
Semantic Task, English
Semantic Task, Consonants
p<0.01

with exemplary English orthography on the one hand, and completely meaningless, orthographically illegal combinations of letters on the other. If the ERPs collected are sensitive to orthographic and/or semantic manipulations, then the contrast of English words vs consonant strings viewed under the demands of the semantic task should demonstrate that sensitivity, and allow us to define where and when these sensitivities occur. This contrast also represents a replication of results reported by Compton *et al.* (1991), and thus allows general predictions to be tested through use of one-tailed tests. To obtain the best possible signal-to-noise ratio for this contrast, data from each of the three testing sessions were averaged together for the purposes of this preliminary analysis only.

Results of the Wilcoxon Signed Rank Test and grand average waveforms contrasting English and consonant strings for each of the 65 channels are presented in Fig. 4. The preliminary analysis demonstrated the earliest significant differences approximately 170 ms after stimulus presentation in posterior channels over the left and right hemispheres during the first negative deflection (N1). ERPs to consonant strings were more negative than ERPs to English words, and this pattern continued until approximately 230 ms. During this time only posterior channels demonstrated significant differences (left posterior channels 30, 31, 34, right posterior channels 38, 42, 43). Later differences, starting at approximately 280 ms appeared in many channels of the array. This later difference was most prominent in posterior channels, which demonstrated increased positivity for consonant strings during the second positive deflection (P2). In the posterior channels, this effect lasted until approximately 360 ms after stimulus onset. However, unlike the earlier N1 effect, the P2 effect was present in many channels of the array, and the polarity of the effect was inverted in frontal channels (posterior channels 16, 17, 20, 21, 23, 25, 26, 27, 28, 30, 31, 34, 35, 36, 37, 38, 39, 40, 41, 43, 44, 46; anterior channels 1, 2, 5, 6, 7, 9, 10, 11, 12, 13, 32, 48, 57, 58, 60, 62).

Design of ANOVA Analyses

A set of summary dependent measures were constructed, based on the results of the preliminary analysis, for the purposes of analyzing orthographic and semantic learning effects within a repeated measures ANOVA analysis. To characterize significant samples from the preliminary analysis, a set of channels were selected that demonstrated the most robust effects both in the N1 and in the P2 time windows. Four channels were selected (channels 30, 31, 38, and 42) such that equal positions over the left and right hemisphere

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FIG. 4. 65-channel average referenced voltage plot of English words and consonant strings viewed under semantic task conditions, averaged over three testing sessions. Markings above the baseline indicate samples that contain significant differences between two conditions, with a threshold of $p < .01$ in a one-tailed Wilcoxon Signed Rank Test.

were included. The circled numbers in Fig. 5A demonstrate the locations of these four channels in the array. Figure 5B demonstrates the average response from these four posterior channels for the purposes of demonstrating the timecourse of the N1 and P2 effect windows. Analyses of the N1 window included samples collected between 170 and 230 ms after stimulus onset. Analyses of the P2 window included samples collected between 280 and 360 ms after stimulus onset.

Values for the four channels of the N1 and P2 windows were entered into two separate repeated measures ANOVAs. These analyses included the factors of training interval (no training, 20 h training, 50 h training), type of task performed (passive, semantic, feature search), and type of stimulus (English, Keki, Keki-control, consonant string). In addition two spatial factors were included based on the position of the recording sensors. These two factors included the hemisphere of the recording site (left, right) and the relative position of the sensor to the midline, termed ‘‘centrality’’ (lateral, medial).

Orthographic Effects in the N1 Window

By the standards of English orthography, stimuli in this experiment contained three levels of orthographic regularity: English stimuli represent orthographically regular strings, the Keki and Keki-control strings reflect a somewhat irregular orthography, and consonant strings reflect orthographically illegal strings. The N1 window contained samples from a portion of the ERP that occurred during the first negative deflection in the posterior channels, briefly after the first negative peak. The size of the deflection from the zero baseline is reported in terms of negative voltage values. Results from the N1 window indicate a significant main effect for the stimulus type factor ($F(3,33) = 10.56$, $p < .01$) that apparently relate to the three levels of orthographic regularity present in these stimuli. Figure 5C demonstrates the means and standard errors from the N1 window. English stimuli elicited the least negative N1, followed by intermediate results for both Keki and Keki-control strings, followed by consonant strings which demonstrated the most negative N1. A set of planned comparisons on the N1 window results confirmed that English orthography elicited less negativity than the illegal orthography of the consonant strings ($F(1,11) = 31.6$, $p < .0001$). Furthermore, strings based on the Keki orthography (including both Keki and Keki control) elicited greater negativity than English ($F(1,11) = 11.139$, $p < .004$), yet still elicited less negativity than the orthographically illegal consonant strings ($F(1,11) = 9.922$, $p < .006$). In general it appears that the greater the orthographic regularity of the letter string, the less negativity occurs in the N1 window.

Stimulus effects were investigated further through a set of planned comparisons designed to separate orthographic effects from other potential effects. Although English, Keki, Keki-control, and consonant strings may differ in many ways in addition to their orthographic differences, direct

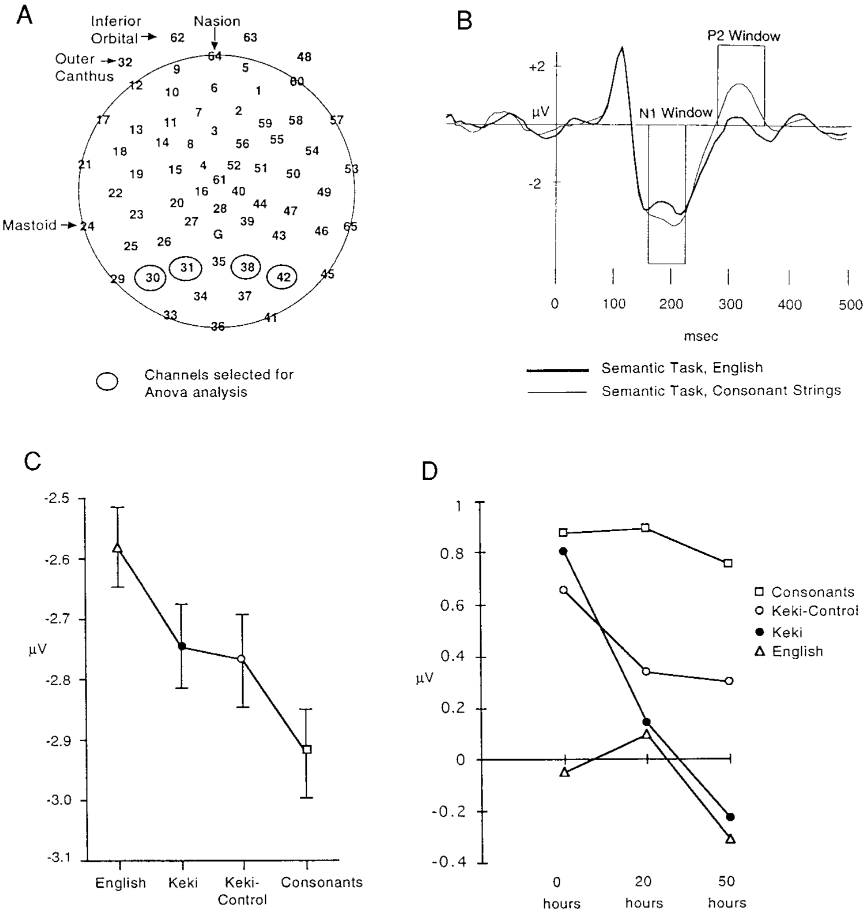

FIG. 5. (A) Diagram of the Series IV 64-channel Geodesic Electrode Net. The large circle represents the location of the adjusted cantho-metal line that circumscribes the head. Positions of the four sensors selected for the ANOVA analyses are indicated by small circles. (B) Enlarged plot of ERP response produced as adult skilled readers viewed English words (thick lines) and consonant strings (thin lines) within the Semantic task. This plot represents an average of the four channels selected for the ANOVA analyses to demonstrates the time general time-course of the effects appearing in the N1 window and the effects appearing in the P2 window. (C) Main effect plot (in μV with standard error bars) demonstrating the mean amplitude between four stimulus groups within the N1 window. (D) Interaction plot (in μV) demonstrating the relationship between mean amplitude in the P2 window and training interval for the four stimulus groups within the semantic task.

comparisons between Keki and Keki-control provide an opportunity to assess the impact of the Keki words becoming familiar and meaningful while holding orthographic regularity constant. The training manipulation changed the familiarity and meaningfulness of the Keki items without changing their orthography. Thus, if the stimulus effects in the N1 window are due to factors other than orthography, such as familiarity or meaningfulness, differences in the N1 window response between Keki and Keki-control should emerge after 50 h of training.

However, a stable pattern emerged across all three visits in which English words produced the least negativity, consonant strings produced the greatest negativity, and Keki and Keki-control produced intermediate negativities which did not differ from other each other.[3] ERP amplitudes in the N1 window demonstrated no effect of learning Keki. After 50 h of training, Keki words in the semantic task produced nearly identical N1 window values as Keki control (mean N1 amplitude for Keki $= -2.876$ micro V, Keki control $= -2.871$ microV). Apparently the ERP responses during the N1 window were influenced by the orthographic regularity of the Keki strings in relation to English orthography. Furthermore, there was no evidence that training resulted in an overall change in the way Keki orthography was processed.

To further understand the role of orthographic and semantic contributions to stimulus effects in the N1 window, it is important to consider the task specificity of the N1 stimulus effects. Results of the N1 window analysis demonstrated a significant main effect for type of task ($F(2,22) = 27.3$, $p < .0001$). Planned comparisons between the task values indicate that the passive task elicited less negativity than either of the two active tasks (passive vs semantic, $F(1,11) = 46.3$, $p < .0001$; passive vs feature search, $F(1,11) = 34.9$, $p < .0001$). However, even though a significant N1 window main effect appeared for both task type and stimulus type, there was no evidence of an interaction. Each task condition produced a similar pattern of stimulus effects in which English words produced the least negativity, consonant strings produced the greatest negativity, and Keki and Keki-control produced an intermediate negativity.

Hemisphere Effects in the N1 Window

An interaction between training and hemisphere ($F = 4.833$, $p < .05$) was present, and is illustrated in Fig. 6. During the initial ERP testing session, before any training took place, N1 window amplitudes were roughly equivalent over left and right hemispheres. However, after 20 h of training the second ERP test revealed that the N1 window amplitude was more negative over left hemisphere channels ($F = 6.637$, $p < .0332$), and this effect was even more robust after 50 h of training ($F = 13.706$, $p < .0057$). This effect demonstrated no significant interactions with any other factors.

As training progressed, the overall magnitude of the N1 window increased

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[3] One exceptional data point to this pattern did exist in the testing session after 20 h of training. While English, Keki, and consonant strings collected after 20 h of training followed the dominant pattern of orthographic regularity (English $= -2.82$ μv, Keki $= -2.86$ μv, consonant strings $= -3.05$ μv), the N1 value elicited by Keki control was equal to the value elicited by consonant strings (Keki control $= -3.05$). However, this value was not significantly more negative than values elicited by Keki strings.

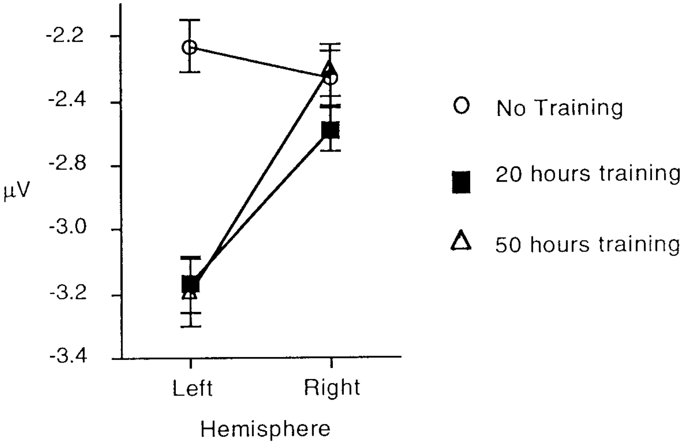

FIG. 6. Interaction plot showing the mean voltages (in μV with standard error bars) for the N1 window, demonstrating the relationship between training interval and hemisphere of recording site.

over the left hemisphere. However, since this effect was not influenced by the type of stimulus presented, it most likely represents changes in the processing strategies that the subjects adopt during each of the three visits. The training manipulation might have made the task more linguistically demanding in the later sessions. Before training, well-known English words were presented in the context of novel nonsense letter strings. However, as training progressed, this context changed. Some of the novel words became familiar words presented in the context of closely matched distractors. Such a shift in context might create different processing demands that result in increased left hemisphere involvement.

Semantic Processing Effects in the P2 Window

The values of the P2 window were collected during the second positive deflection in the posterior channels, and thus increased deflections from the zero voltage baseline are reflected in increasingly positive values. A main effect of stimulus type was present in the P2 window ($F(3,33) = 17.6$, $p < .0001$). Similar to the results of the N1 window, planned comparisons revealed systematic differences across the four stimulus types. English words elicited less positivity than strings that contained Keki orthography ($F(1,11) = 16.1$, $p < .001$), which in turn elicited less positivity than consonant strings ($F(1,11) = 16.7$, $p < .0007$). However, unlike the results of the N1 window, a nonsignificant trend indicated that Keki stimuli elicited less positivity than Keki-control stimuli ($F(1,11) = 3.8$, $p < .07$). Differences between Keki and Keki control could not be accounted for on the basis of orthographic regularity, but could reflect training-induced differences between Keki and Keki control.

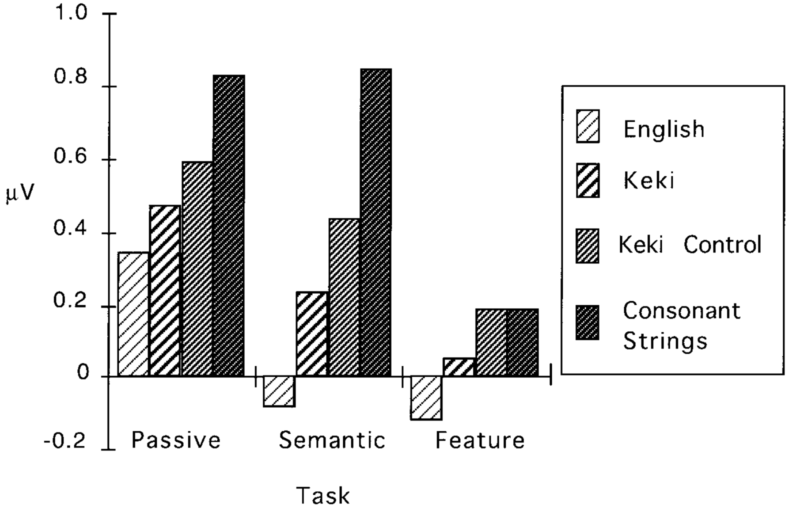

FIG. 7. Interaction plot showing the mean voltages (in μV) during the P2 window, demonstrating the relationship between task and stimulus factors.

To understand the nature of the stimulus effects in the P2 window, it is important to understand how they are influenced by task demands. Analysis of the P2 window data indicate that the task being performed had a substantial impact on the P2 window stimulus effect mentioned above. This robust interaction between task and stimulus type ($F(6,66) = 4.6$, $p < .0005$) is illustrated in Fig. 7. The pattern of stimulus effects observed under passive task conditions is amplified under semantic task conditions. Differences between English words and consonant strings within the passive task are virtually doubled in magnitude when viewed under semantic task demands. The amplification of the stimulus type differences seen in the semantic task cannot be explained in terms of a general increase in task demands, since overall stimulus differences were attenuated in the feature search task which also required actively processing each letter string and making decisions based on information contained in the string. Therefore, it is more likely that the amplification of the stimulus effects under semantic task conditions are related to the specific semantic processes that are recruited by this task.

To test for learning effects, P2 window responses to the four types of stimuli were compared across the three training intervals within the semantic task. Results are illustrated in Fig. 5D. Before training, P2 window responses to Keki stimuli were significantly more positive than responses to English strings ($F(1,11) = 33.0$, $p < .0001$). However, P2 responses to Keki were not significantly different from responses to Keki-control or consonant strings. After 20 h of training, P2 responses to Keki stimuli demonstrated a shift in the direction of English stimuli. Keki words demonstrated significantly less positivity than consonant strings ($F(1,11) = 25.5$, $p < .0005$), and also demonstrated nominally less positivity than Keki control. However, this difference did not reach significance ($F(1,11) = 1.9$, $p < .16$). After 50 h of training, differences in the P2 window between Keki and Keki control stimuli were significantly enhanced. Keki stimuli elicited significantly less positivity than Keki control stimuli ($F(1,11) = 13.1$, $p < .0069$).

Since the orthographic regularity of Keki and Keki control strings were tightly controlled by design and held constant throughout the experiment, orthographic regularity alone cannot account for the stimulus learning effects in the P2 window. It appears that the training procedures led to learning that was specific to the particular Keki items presented, and this learning effect had a systematic influence on the amplitude of the P2 window.

The task by stimulus interaction described above and illustrated in Fig. 7 can be used to help understand the nature of the Keki learning effect. It is possible that the Keki learning effect present in the P2 window is related to nonsemantic effects such as familiarity with the visual codes of each of the learned Keki words. If this is true, the difference between Keki and Keki control should increase with training, but remain relatively independent of the semantic demands of the task being performed. It is also possible that the Keki learning effects are closely related to semantic processing, and thus the difference between Keki and Keki control would increase both as the amount of training increases and as the semantic demands of the task being performed increase.

To examine the relationship between the Keki learning effect and the influence of task demands more generally, responses to Keki and Keki control collected after 50 h of training were examined within the passive and feature search tasks as well. P2 window responses in the passive task revealed that after 50 h of training, Keki words (mean = .48, $SD = 1.1$) were less positive than Keki control (mean = .60, $SD = 1.08$); however, this difference did not approach statistical significance. Similar comparisons within the feature search task after 50 h of training revealed even smaller differences between Keki words (mean = .03, $SD = 1.4$) and Keki control (mean = .19, $SD = 1.5$).

DISCUSSION

The pattern of results in the N1 window suggests that within the first 170 to 230 ms of processing a string of letters, posterior ERPs are substantially influenced by the orthographic regularity of that letter string. The portion of the ERP captured by the N1 window was apparently uninfluenced by the familiarity of a particular letter string. When Keki strings that had been studied for 50 h were directly contrasted with Keki control strings which had no significant learning, mean responses were nearly identical. This pattern of results fits with reaction time studies of visual matching tasks. Carr, Posner, Pollatsek, and Snyder (1979) found that decisions about the visual codes of words, pseudowords, and consonant strings were influenced by orthographic regularity, but not by the familiarity of the letter strings. The nature of the visual matching task suggests that subjects base their decisions on visual codes, and thus orthographic regularity might have an influence on the process of forming a visual code of a letter string.

Overall, it appears that the N1 window reflected orthographic learning of the English language that took place before subjects entered the study. However, the N1 window did not demonstrate learning effects for specific Keki words or general aspects of Keki orthography.

In contrast, the P2 window demonstrated robust learning effects related to changes in the way Keki words were processed between 280 and 360 ms (see Fig. 5D). Over the course of 50 h of training, P2 window responses to Keki words in the semantic task eventually came to resemble English words, while P2 responses to Keki-control strings remained fairly stable across the 5 weeks of training. This suggests that the P2 window results index a form of item-specific learning. Interactions between stimulus type and task in the P2 window suggest that Keki learning is related to processes associated with semantic access. The differences between stimulus types observed under passive task conditions are virtually doubled under the semantic task conditions (see Fig. 7). This effect might reflect increases in semantic processing demands, since the semantic task requires an active judgment about the meaning of the string. It is unlikely that this amplification of stimulus main effects is attributable solely to the fact that the semantic task requires an active decision about the string, while the passive task does not. The feature search task also requires an active decision about the string, yet under feature search task conditions the differences between stimulus types are attenuated.

GENERAL DISCUSSION

This study explored the role of learning on the brain mechanisms involved in orthographic processing and semantic access. Below we consider the implication of our findings for the componential analysis of reading.

Processing Visual Codes

The general pattern of the N1 ERP window was consistent with PET research demonstrating a left medial extrastriate region that is sensitive to the orthographic regularity of letter strings, yet is insensitive to the lexical status of the string. Taken together, the PET and ERP results suggest that an extrastriate cortical area is involved in the initial encoding of letter features together into a unified representation. This process is clearly influenced by learning to read. However, the results of our learning manipulation suggest that orthographic learning processes in adult readers are not easily modified. Fifty hours of exposure to the unique orthography of the Keki language had no measurable impact on the ERPs recorded in the N1 window. Since the Keki orthography was only slightly different than English orthography we do not know if the same would apply to a distinctly different orthography.

Processing Word-Specific Information and Semantic Codes

The behavioral reaction time results of the matching task indicated a specific benefit for English words over Keki control at each test interval. This task was designed to discourage subjects from making match decisions on the basis of visual codes by introducing a delay between the two stimuli, masking the first stimulus, and presenting the strings in opposite letter cases. Thus, subjects needed to rely on another form of representation. Reaction times after 50 h of training for Keki words became equivalent to high frequency English words.

During the P2 window of the ERP, evidence for item-specific learning of the Keki words emerged over the course of 50 h of training. The differences in amplitude that emerge over the course of Keki training occur only for the familiar Keki strings and not for the unfamiliar Keki controls created by the same orthographic system. This Keki learning effect is a clear indication that subjects have internalized some form of mental representations specific to the Keki words, and they are able to access these representations within 280 ms. Some aspects of the ERP results also suggest that the Keki learning effects could be related to semantic processing. In addition to gaining a great deal of visual familiarity with the specific Keki words, subjects also learned the meanings associated with each Keki word. A role for semantic access in the P2 window is supported by the nature of the stimulus task interaction. Under passive conditions, the difference between Keki and Keki control is rather small, but this difference is amplified under semantic task conditions and attenuated under feature search task conditions.

This task by stimulus interaction directly parallels the effects of manipulating the task applied to a prime in the semantic priming studies discussed in our introduction. When primes are passively viewed, semantic priming is typically observed. However, when attention is focused on the meaning of a prime, semantic priming is enhanced over passive processing conditions. When attention is focused on a sublexical aspect of the string, semantic priming is attenuated. This parallel suggests that ERP measurements in the P2 window reflect processes related to accessing semantic information.

Converging evidence from PET, semantic priming, and visual matching tasks has led us to emphasize visual-orthographic and semantic processes in our interpretation of the Keki learning effects. However, we should note that such effects could also be consistent with interpretations that focus on phonological processes in word identification (Lukatela & Turvey, 1990; Perfetti & Zhang, 1995; Van Orden, Pennington, & Stone, 1990). For example, it is possible that N1 effects are influenced by phonological recoding and that P2 effects related to learned Keki words reflect activation of word-specific phonological codes. Although this study was not designed to test distinctions between such interpretations, our approach of using miniature artificial languages to trace learning over time could provide unique avenues to directly address such issues.

In general, the ERP results reflect several findings related to the impact of learning on the underlying brain circuitry that supports visual word recognition. Apparently encoding processes of adult skilled readers are sensitive to the orthographic regularity at an early time following input and in a location that is visually specific. Orthographic effects support the notion that readers eventually internalize the regularities inherent the structure of written words.

Development of orthographic encoding mechanisms is an important aspect of word recognition skill that allows readers to process words rapidly. Results of the Keki learning experiment suggest that orthographic processes operate quite early during word recognition (within 170 ms), but that these processes are slow to change. Relatively little is known about how such skills develop when literacy in a language is initially acquired. Understanding how such processes are best developed through learning experiences could hold important insights into acquisition of reading skill.

APPENDIX

List of the Keki Vocabulary Words and Their English Translations

bakso = table
beme = say
binde = drive
birno = fruit
brope = hit
bune = stand
dalko = letter
dimo = soup
diste = catch
drosto = food
druka = long, tall
duko = window
dalko = letter
famso = store
feno = ball
firne = write
fune = give
galto = pen
gilki = bird
gonta = happy
kale = sit
kezo = tree
kisko = paper
klano = house
klito = book
krule = eat
kunda = big

kurso = chair
lanso = water
leke = go, walk
liska = short
lompo = picture
luti = boy
mako = stick
menti = woman
monde = come
muble = want
mula = white
nake = start
nembe = drink
nosko = wall
noti = girl
nusti = cat
pame = do
penka = black
plune = buy
prano = car
preto = fire
pule = hold, take
raste = read
sasi = dog
sluka = bad
sopla = small
sulo = male

sumpe = throw
suta = angry
tane = be
tanti = man
teka = good
tibe = see
tilko = door
tonde = put
trazo = pot
tuso = bread
zalo = hand
zempo = cup
ziko = hat
zoke = break

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